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Key Points:
- We analyze the future coevolution of an irrigated agricultural district under climate change
- We advance the representation of human behaviors to better describe feedbacks between natural and human components of CHNS
- We study how the coadaptation of water supply and demand removes policy inertia

Supporting Information:
- Supporting Information S1

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A coupled human-natural systems analysis of irrigated agriculture under changing climate

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Abstract Exponentially growing water demands and increasingly uncertain hydrologic regimes due to changes in climate and land use are challenging the sustainability of agricultural water systems. Farmers must adapt their management strategies in order to secure food production and avoid crop failures. Investigating the potential for adaptation policies in agricultural systems requires accounting for their natural and human components, along with their reciprocal interactions. Yet this feedback is generally overlooked in the water resources systems literature. In this work, we contribute a novel modeling approach to study the coevolution of irrigated agriculture under changing climate, advancing the representation of the human component within agricultural systems by using normative meta-models to describe the behaviors of groups of farmers or institutional decisions. These behavioral models, validated against observational data, are then integrated into a coupled human-natural system simulation model to better represent both systems and their coevolution under future changing climate conditions, assuming the adoption of different policy adaptation options, such as cultivating less water demanding crops. The application to the pilot study of the Adda River basin in northern Italy shows that the dynamic coadaptation of water supply and demand allows farmers to avoid estimated potential losses of more than 10 M€/yr under projected climate changes, while unilateral adaptation of either the water supply or the demand are both demonstrated to be less effective. Results also show that the impact of the different policy options varies as function of drought intensity, with water demand adaptation outperforming water supply adaptation when drought conditions become more severe.

1. Introduction

With one quarter of harvested cropland under irrigation [*Portmann et al.*, 2010], the agriculture sector is the world's largest consumer of water [*Ferrant et al.*, 2014]. Global change will soon increase this consumption: to meet projected growth in human population and per-capita food demand [*Gerland et al.*, 2014], agricultural production will significantly expand in the coming decades, mostly through irrigated crops, inducing a considerable rise in water demand [*de Fraiture and Wichelns*, 2010; *Sauer et al.*, 2010]. On the other hand, water availability, which is often a key factor in determining crop productivity [*Siebert and Döll*, 2010], is projected to decrease in many regions due to climate change impacts [*Gornall et al.*, 2010; *Iglesias and Garrote*, 2015]. The increase of temperature extremes will further decrease crop yields [e.g., *Battisti and Naylor*, 2009; *Lobell et al.*, 2011]. This expected Malthusian trap of diverging water supply and demand [*Nelson et al.*, 2010] calls for adaptation policies to produce "more crop per drop" [*Marris*, 2008] and to quickly recover to adequate levels of productivity from situations of unpredictable stress, resulting from price volatility or intense droughts [*Ahmed et al.*, 2009].

Investigating the opportunities and vulnerabilities of alternative climate change adaptation policies requires advancing our understanding of the complexity and flexibility of agricultural systems, explicitly accounting for their natural and human components, along with their interactions. Human decisions made by farmers and water supply operators impact on the natural system by determining cropping patterns, water allocation, and residual flow in the river. In turn, the natural system responds to these decisions directly through hydroclimatic conditions, such as freshwater availability, rainfall, or temperature, as well as indirectly through ecosystem services, including soil retention, regulation of soil fertility, or nutrient cycling [*Power*, 2010]. These interactions between humans and nature were generally overlooked in the water resources

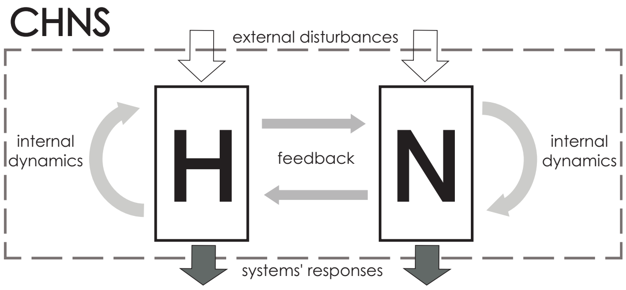

Figure 1. Conceptualization of Coupled Human-Natural Systems adapted from *Polhill et al*. [2016]. The human (H) and natural (N) systems are represented as boxes with the light gray arrows showing reciprocal interactions and feedbacks. These three components are surrounded by a dashed line, representing a single modeling framework, which is exposed to external drivers and produces the system response.

systems modeling literature [*Sivapalan et al*., 2012], where, until a few years ago, the focus was mostly on understanding and studying the natural processes only [e.g., *Dooge*, 1959], assuming one or few scenarios of human actions treated as fixed boundary conditions [e.g., *Sivakumar et al*., 2005; *Cooper et al*., 2008]. Nowadays this unilateral perspective might no longer be appropriate [*Thompson et al*., 2013] and a paradigm shift is required to put humans in the modeling loop. To respond to this demand, a number of conceptual framework have been recently proposed, including Coupled Human-Natural Systems (CHNSs) [*Liu et al*., 2007], Social-Ecological Systems [*Anderies et al*., 2006], Socio-Environmental Systems [*Filatova et al*., 2016], and Socio-Hydrology [*Sivapalan et al*., 2012]. These frameworks aim to study complex systems composed by a natural and a human component, their reciprocal interactions and feedbacks, and their coevolution in time [e.g., *Horan et al*., 2011; *Elshafei et al*., 2015; *Sivapalan and Blöschl*, 2015; *Polhill et al*., 2016]. This requires developing integrated models (see Figure 1) which comprise a model of both the natural processes and the human processes, i.e., human behaviors, explicitly accounting for their interactions.

While mathematical models of natural processes have been studied and developed for centuries [e.g., *Mulvaney*, 1851; *Kuichling*, 1889] and, today, they are extremely sophisticated at fine spatial and temporal scales [*Washington et al*., 2009], the literature about human behavioral models is much younger and less developed. We can broadly distinguish two main categories [*Smith*, 1991]: descriptive models, which display the decision mechanism, and normative models, which focus on motivation-based actions. Descriptive models are mainly developed in cognitive psychology and social sciences [e.g., *Kahneman and Tversky*, 1979; *Camerer et al*., 2011] and infer behavioral rules from observational data or general theories. Many environmental applications have adopted this approach, particularly for implementing agent-based simulation models in order to evaluate macrolevel properties emerging from lower-level interactions among the agents [e.g., *An*, 2012; *Berglund*, 2015]. The resulting models generally include a large number of assumptions and parameters, which, in the absence of a proper validation against observational data, limit the reliability of the models' outputs [*Ligtenberg et al*., 2010]. Normative models are primarily developed in economics [*Becker*, 1978] and assume that human decisions are designed to maximize a given utility function (i.e., fully rational behavior). Although this hypothesis has been often contradicted by observations of real behaviors [*Simon*, 1957], this second approach has been largely adopted in environmental applications with prescriptive purposes, especially for designing decision support systems which provide optimal decisions with respect to the formulated maximization problem [e.g., *Loucks et al*., 2005; *Poff et al*., 2015].

In this work, we attempt to improve the representation of CHNSs by turning normative approaches into descriptive tools, where the ultimate goal is not to predict the optimal human decisions to be taken in the future, but instead to understand how all components of a CHNS coevolve when exposed to altered boundary conditions [*Sivapalan and Blöschl*, 2015]. We argue that the full rationality assumption could be acceptable in this normative meta-modeling approach, where we are describing institutional decisions or average behaviors of groups of individuals (e.g., group of farmers organized as districts or irrigation units). For example, although it is generally possible to observe irrational behaviors at the individual-farmer level, such irrationality is filtered when considering the decisions at the district level. Hence, assuming that the utility functions (e.g., profit maximization) are able to capture the real interests driving the observed behaviors, then the future behaviors will be correctly reproduced by solving the same maximization problem, which is generating the present behavior, under different boundary (e.g., climate) conditions. On the contrary, a behavioral rule inferred from historical data is not guaranteed to hold under altered conditions. In other words, we can assume the farmers will maximize their profit also in the future, but we cannot ensure they will maintain the same behavioral rule to meet that target. To demonstrate the potential of this normative meta-modeling approach, we also perform a validation of the modeled human behaviors against observational data, as it is common practice for models describing natural processes.

This idea is implemented through a simulation-based integrated modeling framework, which allows capturing the coupled human and natural systems interrelationships as well as reproducing the impacts of exogenous drivers and internal feedbacks on the system dynamics [*Cai*, 2008]. This integrated framework improves our ability of describing potentially nonlinear, out-of-equilibrium, adaptive dynamics of the modeled CHNSs [*Folke*, 2006]. The latter cannot be captured by traditional hydroeconomic models [e.g., *Pulido-Velazquez et al*., 2008; *Harou et al*., 2009] as they generally deal with marginal changes around an equilibrium, in many cases necessarily reconstructed from historical data [*Stern*, 2008]. Moreover, replacing the prescriptive use of such integrated models, which is typical of the current Integrated Water Resources Management literature, with a descriptive point of view allows gaining insights on the main processes driving CHNSs present dynamics and inspiring the development of more reliable and credible projections about their future coevolution [*Wagener et al*., 2010; *Srinivasan et al*., 2012].

We demonstrate the potential of our approach by developing an application to the pilot CHNS of the Adda River basin, in northern Italy. This CHNS includes the regulated Lake Como and a large irrigated area downstream from the lake, comprising four agricultural districts fed by an extensive network of irrigation canals. The lake regulation is primarily targeted to irrigation supply, along with other operating objectives, such as flood control and environmental protection. In particular, the lake is operated to satisfy a nominal irrigation water demand, defined as the aggregation of the historical water rights of the downstream water users (farmers and hydropower companies). These water rights, which were originally established in 1942 and only marginally modified afterward, represent the irrigation water requirements under "normal" conditions and do not account for the type of crops cultivated or the meteorological conditions actually occurring in a specific year. Historically, this lack of integration has not been a severe limiting factor for the development of agricultural activities in the Adda River basin, due to favorable hydrological conditions. However, in recent decades, climate change has already shown its potential negative impact in a number of situations [e.g., *García-Herrera et al*., 2010], with the frequency and intensity of water crises expected to increase over the next years [*Lehner et al*., 2006; *Forzieri et al*., 2014]. For example, two severe droughts in 2003 and in 2005 generated acute system failures and exacerbated the conflicts between agriculture and the other sectors, ultimately generating significant economic losses along with negative impacts on the environment [*Anghileri et al*., 2013]. By contrasting the response of the CHNS to different adaptation policy options, we can explore the potential cobenefit of a more dynamic and flexible management of the human-nature interactions, where water services effectively match the real needs of the final users and adapt to ongoing changes.

In practice, policy changes usually occur only when the frequency and the magnitude of failures become socially and/or economically unsustainable [*Adger et al*., 2005; *Tompkins*, 2005]. As water institutions' responses to changing boundary conditions are often disaster-driven [*Gardiner*, 2009], current management practices are generally revised only when dramatic failures, disasters, or catastrophes occur [e.g., *Comfort et al*., 1999; *Birkland*, 2006]. Moreover, the stratification of agreements and regulatory constraints from the farm to the basin level often creates policy inertia [*Sheer*, 2010; *Giuliani et al*., 2014], which further hampers the change of historical practices. This inertia facilitates the conservation of the status quo and slows down the rate of convergence to a new equilibrium, ultimately causing the system to underperform for several years before reaching a new steady state [*Adger et al*., 2009; *Moser and Ekstrom*, 2010].

To explore the response of the Adda River basin under increasingly challenging conditions, characterized by more frequent and intense droughts, we consider both current and projected climate conditions as provided by the A2 emission scenario simulated with the HadAM3H/RACMo circulation models, which was demonstrated to negatively impact this river basin in prior work [*Anghileri et al*., 2011]. We analyze alternative policy adaptation options relying on different levels of coordination, which may represent promising flexible and low-cost alternatives that do not require any investment in infrastructural changes (e.g., capacity expansion or modification of the irrigation canals). These policy options range from a baseline solution, where both the lake operator and the farmers are inertial and insensitive to the changing conditions, to a complete coadaptation of both water supply and demand, where the downstream water allocations change seasonally according to the actual cropping patterns and water supply is adapted to the new water allocation plans. This fully integrated option represents an upper bound solution, which activates a feedback loop between water supply, water demand, and the underlying natural conditions. Water supply management strategies are designed according to both the climate conditions and the actual water requirements of the cropping pattern expected in the next agricultural season. At the same time, these cropping patterns are selected by the farmers as the most profitable under the considered climate and the expected water availability, which is, in turn, dependent on the water supply management. Finally, given the long-term perspective of the analysis, we also explore possible dynamic changes in the preferences of the lake operator, expressed in terms of modification of the historical compromise balancing irrigation supply and flood control. In fact, extreme variability in the system's drivers might affect the preferences driving human decisions [*Amigoni et al.*, 2016; *Giuliani and Castelletti*, 2016]. Accounting for such potential changes due to human-nature interactions and feedbacks is a key for properly representing the coevolution of CHNSs [*Caldas et al.*, 2015; *Sivapalan and Blöschl*, 2015].

In summary, this paper provides two main contributions: a novel modeling approach to study the coevolution of irrigated agriculture under changing climate, advancing the representation of the human component by using normative meta-models to describe the behaviors of groups of farmers or institutional decisions; and a policy analysis contribution, where the proposed model is used to assess the space for improving water management practices and overcome the limitations of policy inertia, ultimately compressing the time of the transition toward more efficient water management solutions.

The paper is organized as follows: the next section introduces the study site, followed by a description of the modeling approach. Results and discussion are then reported, while final remarks, along with directions for further research, are presented in the last section.

2. Study Site

The Adda River, the fourth longest Italian river, is a tributary of the Po river which flows into Lake Como, a regulated lake in northern Italy with an active storage capacity of 254 Mm^3 fed by a 4552 km^2 catchment (Figure 2). The hydro-meteorological regime is typical of alpine regions, characterized by dry periods in winter and summer, and peaks in late spring and autumn fed by snowmelt and rainfall, respectively. Downstream from the lake, the Adda River feeds eight run-of-the-river hydroelectric power plants and serves a dense network of irrigation canals belonging to four irrigation districts, with a total irrigated area of 1400 km^2. The operations of the lake aim also to prevent flooding along the lake shores, particularly in the city of Como, and to protect the ecological conditions both of the lake and of the downstream stretch of the Adda River. This environmental interest is partially represented by a minimum environmental flow constraint that the lake release must satisfy.

Among the irrigation districts served by the Adda River, in this work we focus on the Muzza district, located southeast of the city of Milan (Figure 2). This district was selected because it is the largest among the irrigation district served solely by the Adda River (about 700 km^2) and is the one with the largest water concession (2370 Mm^3/yr). Major cultivated crops are maize and temporary grasslands, while minor crops include rice, soybean, wheat, tomato, and barley. Crop productions are very high, with yields of 12 t/ha for maize and 50 t/ha for temporary grasslands [*Pieri and Pretolani*, 2013] and are largely dependent on irrigation, which is applied with the border method. Such maize and grasslands dominated cropping patterns are widely diffused in the Po valley due to the livestock-oriented nature of the agricultural production systems in the area. The district is organized in 39 irrigation units, each including a number of farms, which receive a continuous water supply through an extensive irrigation network (more than 4000 km in total length).

The current irrigation management is based on a three-level structure, which involves the farmers, the irrigation districts, and the lake operator. At the beginning of each irrigation season, the farmers negotiate with the irrigation districts the seasonal water supply. The farmers' requests are generally based on historical water rights and do not change significantly from year to year. Then, each irrigation district manages the water diversions from the Adda River as well as the conveyance and distribution of the diverted water to the individual farmers. Such distribution is organized according to a rotation scheme and, in each turn (i.e., 7–14 days depending on soil and crop characteristics), farmers receive the negotiated discharge for a fixed number of hours. The interactions between irrigation districts and the lake operator are generally limited in normal years, when the districts simply communicate to the lake operator the volume of water they diverted. In drought years, they are instead called to negotiate a curtailment of the farmers' water supply. Curtailment is then implemented according to a water banking mechanism to guarantee that the seasonal

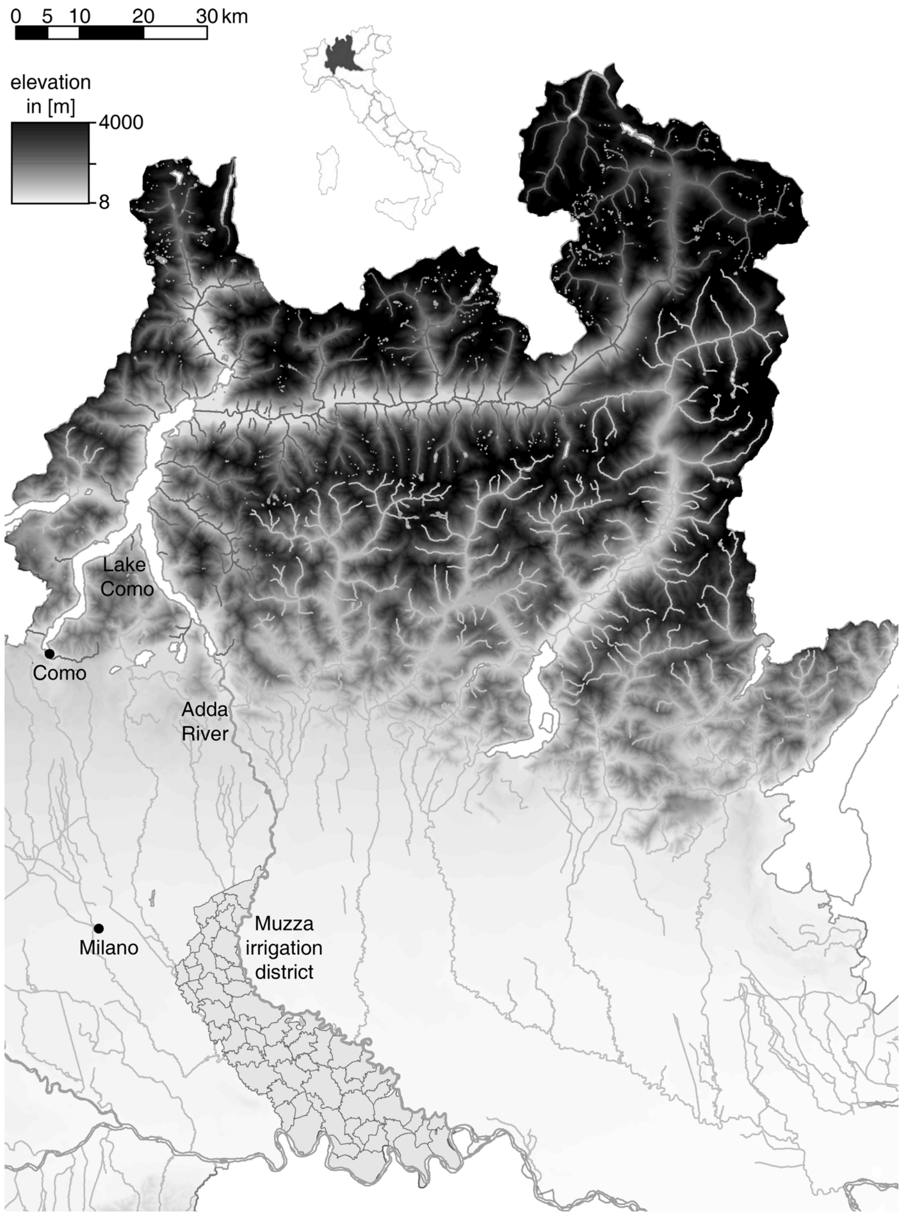

Figure 2. Map of the Adda River basin: Lake Como, Adda River, and the Muzza irrigation district.

volume of water delivered to each district is proportional to the allocation established at the beginning of the season. In this case, each irrigation district informs the farmers about the modifications of the normal irrigation schedule (e.g., extension of the rotation period) that will be in place during the drought period. This management structure has been running for the last seventy years and the underlying coordination mechanisms between farmers, irrigation districts, and lake operator are well established. This offers a consolidated basis for the implementation of the proposed policy adaptation options, including the unilateral water supply adaptation option, the unilateral water demand adaptation, and the coadaptation of both water supply and demand (see section 3.3).

Historically, water availability has not been a major limiting factor for the development of regional water-related activities; management practices, even though mostly uncoordinated, have generally satisfied all competing demands. As a consequence, the opportunity of improving system performance through a better integration of water demand and supply in the management process has long been overlooked. Yet a nonstationary trend has already manifested its negative impacts on the Adda River basin as demonstrated,

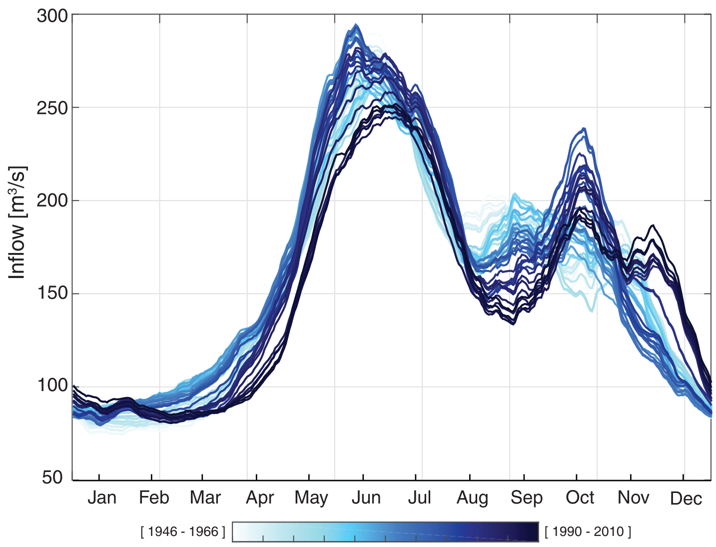

Figure 3. Trend analysis of the daily inflows over the time horizon 1946–2010: the average is computed by means of a moving window that includes data over consecutive days in the same year and over the same days in consecutive years, with the window progressively shifted ahead to identify long-term trends. In the figure, each line represents a 20 years moving average, from the 1946–1966 (light blue) to the 1990–2010 (dark blue) time horizons.

for example, by the alteration of the hydrological regime of the Lake Como inflows. Figure 3 visualizes the trend in the inflows observed over the last 60 years using the MASH tool [*Anghileri et al.*, 2014], which enables assessing variations in the seasonal pattern of the flow represented by the 365 values of average daily flow over the year. The inflows show a clear decreasing tendency during the late spring and summer periods, which are the most critical for irrigated agriculture. Should this trend continue over the next years, the adoption of some adaptation strategies will be unavoidable to prevent the failures experienced during the recent droughts of 2003 and 2005.

3. Models and Tools

Most of the studies assessing climate change impacts on agricultural systems focus either on water demand or water supply adaptation strategies independently, without exploring their interactions and their relationships with the undergoing natural processes [*Howden et al.*, 2007]. Farmers' practices are generally studied assuming one or few scenarios of projected water availability [e.g., *Rosenzweig et al.*, 2004; *Marques et al.*, 2010; *Ng et al.*, 2011], while water supply management strategies are often analyzed against a single or a small number of water demand scenarios [e.g., *Schoups et al.*, 2006; *Hingray et al.*, 2007; *Medellín-Azuara et al.*, 2008].

To characterize the variety of decision-making authorities acting in the Adda River basin (i.e., farmers and the operator of Lake Como) and to analyze the effects of the different policy adaptation options to the changing climate, we developed an integrated model of the Adda River basin (Figure 4), which includes a lumped, conceptual rainfall-runoff model of the upstream catchment [*Bergström*, 1976]; a mass balance model of the Lake Como dynamics subject to human regulation [*Hashimoto et al.*, 1982; *Piccardi and Soncini-Sessa*, 1991; *Galelli and Soncini-Sessa*, 2010; *Anghileri et al.*, 2011; *Giuliani and Castelletti*, 2016]; a routing model of the water released from the lake outlets to the intake of the irrigation canals; and a spatially distributed agricultural model simulating soil-crop water balance, crop growth stages, and final yield in each irrigation unit of the Muzza district [*Doorenbos et al.*, 1979; *Allen et al.*, 1998; *Facchi et al.*, 2004; *Gandolfi et al.*, 2006; *Steduto et al.*, 2009; *Neitsch et al.*, 2011]. Further details about the different model components are provided in the Supporting Information.

3.1. Normative Meta-Models of Human Behaviors

The water supply decisions for the regulation of Lake Como are modeled as a daily operating policy π^*, which provides the volume of water to be released over the next 24 h as a function of the observed lake storage and the day of the year, subject to a minimum environmental flow constraint to protect the downstream river ecosystems. Such operating policy is obtained by formulating and solving a stochastic, periodic, nonlinear, closed-loop optimal control problem [see *Castelletti et al.*, 2008, and references therein], subject to the dynamic constraints given by the system's dynamics

$$\pi^* = \arg\min_{\pi} J_S(\pi, w). \tag{1}$$

The lake operator's objective $J_S(\pi, w)$ depends on the operating policy π, which determines the release from the lake and, consequently, the flow diverted in the Muzza canal, and on the downstream water

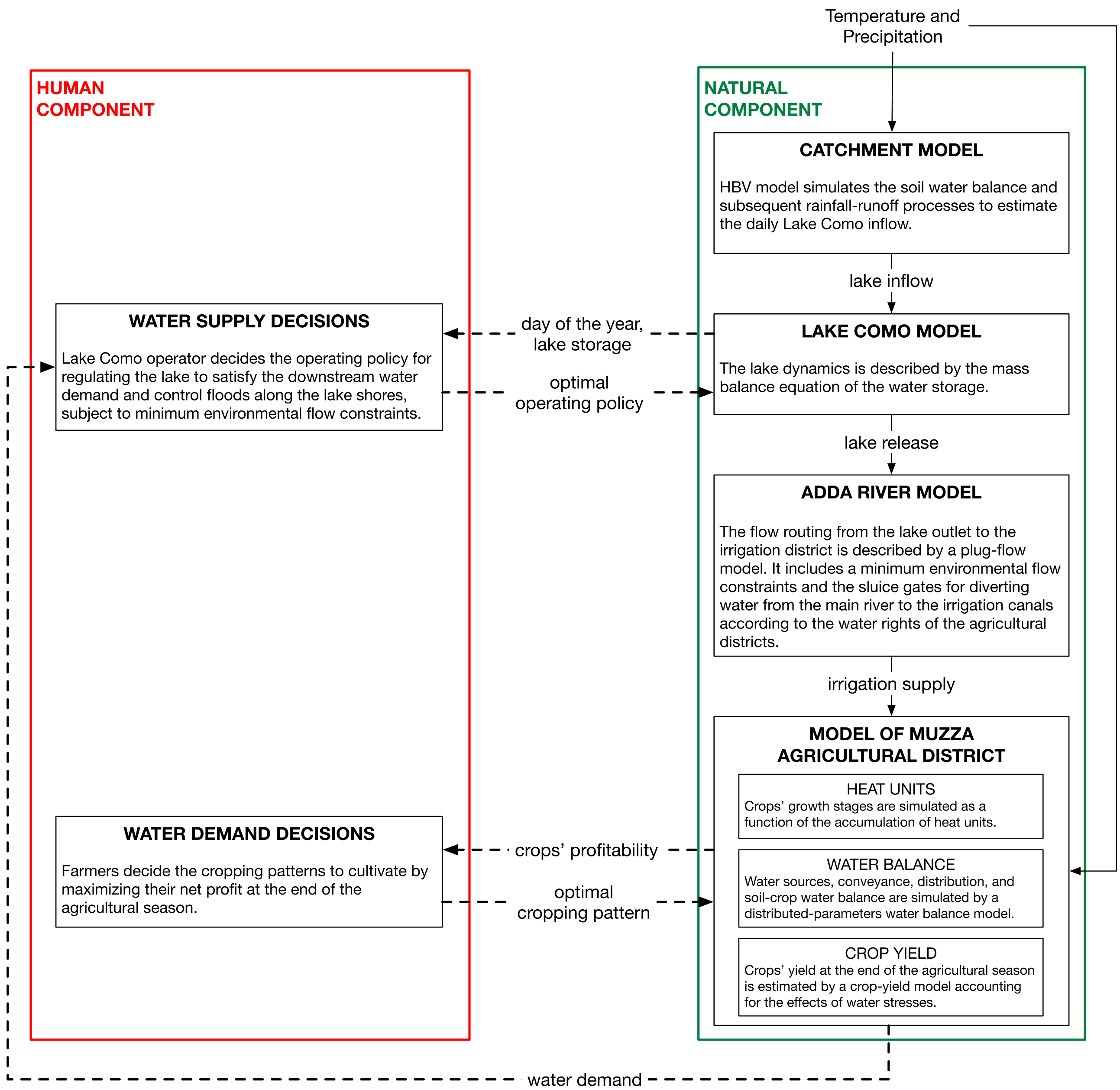

Figure 4. Schematic representation of the Adda River basin integrated model, where the dashed lines show the complex network of feedbacks between the human and the natural component of the system and between the water supply and water demand decisions.

demand w, which varies with the cropping pattern cultivated in the Muzza district. Formally, $J_S(\pi, w)$ is a convex combination of two objective functions accounting for flood control (J^{flood}, measuring the daily average flooded surface in Como, to be minimized) and water supply vulnerability (J^{def}, measuring the quadratic daily average water deficit with respect to the downstream water demand, to be minimized). We consider both an aggregation of J^{flood} and J^{def} where the weights were estimated to reproduce the historical tradeoff, and a number of alternative combinations to explore potential dynamic changes in the preferences of the lake operator.

The water demand decisions are the cropping patterns to be cultivated in the Muzza district selected by the farmers prior the beginning of the agricultural season. These decisions are modeled as the cropping pattern γ_k^* for the kth farmer ($k=1,\ldots,N$) characterized by the highest expected profitability, obtained by solving N nonlinear optimization problems formulated as follows:

$$\gamma_k^* = \arg\max_{\gamma_k} J_k^D(Y(\gamma_k), p(\gamma_k), c(\gamma_k), \sigma(A_k), \pi) \qquad k=1,\ldots,N. \tag{2}$$

The farmers' objective J_k^D of the kth farmer depends on the yield of the cultivated crop $Y(\gamma_k)$, the associated crop price $p(\gamma_k)$, cost $c(\gamma_k)$, the subsides $\sigma(A_k)$, and the water supply operating policy π, which defines the lake regulation and determines the water available for irrigation. The subsidies $\sigma(A_k)$ derive from the EU's Common Agricultural Policy (CAP), which complements a system of direct payments to farmers with measures to help rural areas in facing a wide range of economic, environmental, and social challenges [*Britz et al.*, 2003]. These subsidies depend on the cultivated area A_k and not on the selected type of crop γ_k [*Gandolfi et al.*, 2014].

In the formulation of Problem (2) we introduced the simplifying assumptions that the decision of each farmer is limited to a single crop in each agricultural season and the farmers have a perfect forecast of the socio-economic and hydroclimatic conditions when they decide the most profitable crop to grow. The performance obtained under these ideal conditions will obviously degrade when moving to uncertain forecasts. However, this does not undermine the significance of a comparison between the different adaptation policy options based on the relative difference of performance rather than on their absolute value. In addition, the modeled farmers do not represent individual farmers in the system, but rather the entire group of farmers in one of the 39 irrigation units. This hypothesis is tantamount to describing the median behavior of the ensemble of farmers aggregated at the irrigation unit level, and provides a simple and effective way to capture the interannual dynamics of land use at the district scale, where such group decisions can be effectively described by our normative meta-modeling approach under the assumption of rational behaviors.

3.2. Modeling Human-Nature Feedbacks

The normative meta-models introduced in equations (1) and (2) show the interdependency between the behaviors of the lake operator and farmers. Note that these decisions are characterized by different time scales: farmers make seasonal decisions to maximize their expected net profit, while the lake is operated daily to balance water supply and flood protection, subject to environmental flow constraints. To effectively cross condition the two normative meta-models, we propose a coadaptation option based on the activation of an information loop for coordinating water demand and supply decisions. This mechanism implies negotiating and revising the water allocation plan of the downstream users at the beginning of every agricultural season on the basis of the selected cropping pattern and adapting the daily water supply operations to the estimated water demand. Since farmers' decisions depend on the expected water availability, which is affected by the water supply operations, the coadaptation option activates an iterative process.

At the generic iteration j of the coadaptation loop, the optimal operating policy π^j of the Lake Como is determined on the basis of the downstream water demand w^j. Then, the water supply system regulated according to π^j is simulated over a time horizon of one agricultural season in order to obtain the trajectories of the expected lake releases and the water available for irrigation q_{irr}^j on a daily basis. The latter is used as input for the model of the water demand subsystem, which allows the simulation of the water distribution to each irrigation unit and the computation of the spatially distributed hydrologic balance in the root zone for each cell of the Muzza district, taking into account the different crops' growth stages. For a given q_{irr}^j, each farmer optimizes the cropping pattern γ_k^j for the coming agricultural season, namely the one producing the highest expected net profit. In addition, the model estimates the water requirements of the crops cultivated in each irrigation unit, from which a new total water demand can be estimated (i.e., $w^{j+1}=\sum_{k=1}^{N} f(\gamma_k^j)$). The procedure is iterated by refining the operating policy of the lake π^{j+1} to better match the updated downstream water demand w^{j+1}. This coadaptation loop is initialized by designing the Lake Como operating policy with the historical nominal water demand, while the loop is stopped when the system reaches an equilibrium. We assume that convergence is obtained when the number of farmers changing crop decisions between two consecutive iterations is lower than a desired fraction of the total number of cells of the spatial domain, set equal to 20%.

This coadaptation loop allows cross-conditioning water supply and demand decisions. These human decisions both depend on, and impact, the natural component of the CHNS. The flow in the Adda River downstream from the lake, which is regulated by the operating policy, strongly depends on the lake storage and, consequently, on the lake inflow from the upstream catchment. Similarly, the crop growth processes in the Muzza district depend on the irrigation supply and the selected cropping pattern as well as on the meteorological conditions. In turn, the human decisions have direct impacts on the environment, potentially altering the ecosystems both in the lake and in the downstream river. Such complex network of feedbacks is summarized in Figure 4 (see the dashed lines).

3.3. Climate Scenarios and Policy Adaptation Options

Two climate scenarios are considered in this work, namely current and projected conditions. The projected time series of climate variables under climate change conditions are obtained by applying a cascade of models: the A2 emission scenario provided by the Intergovernmental Panel on Climate Change [*IPCC*, 2000] is used as input to a general circulation model (GCM), which provides the boundary conditions for a regional circulation model (RCM). In particular, we used the GCM HadAM3H [*Pope et al*., 2000] and the RCM RACMo [*Lenderink et al*., 2003]. This combination of emission scenario and global/regional models has been demonstrated to produce significantly negative impacts on the system under study [*Anghileri et al*., 2011].

Since the spatial resolution of RACMo is too coarse to provide representative climate scenarios at the basin scale, a statistical downscaling method based on quantile mapping [*Déqué*, 2007; *Boé et al*., 2007] was applied to correct RCM outputs at the catchment scale. A site-specific quantile-quantile correction function is estimated by comparing historical measured data with the outputs obtained from RACMo simulations over the historical control period (i.e., 1961–1990). By assuming that this relationship will not change in the future, this function can be applied to the RACMo output over the projected period (i.e., 2071–2100). The downscaled variables are then used as input for the catchment model to obtain the projected time series of Lake Como inflows. The data used for the downscaling were obtained from the PRUDENCE project [*Christensen and Christensen*, 2007].

The set of policy options available for implementing adaptive management strategies comprises, on the water supply side, the modification of Lake Como operating policy and, on the water demand side, the farmers' decisions of the crops to grow. We consider the four most common crops in the Pianura Padana agricultural systems, namely maize, rice, soybean, and tomato, along with a fixed area of the Muzza district devoted to the cultivation of temporary grasslands (mainly alfalfa) due to the high livestock density in the district. We focus on these crops as they were suggested as interesting alternatives by the stakeholders given the Italian agro-economic system. We investigate four alternative levels of policy adaptation: (i) a baseline option which maintains the current management practices with no adaptation of either the lake regulation or the cropping pattern; (ii) unilateral water supply adaptation option, where the water supply operations are adjusted to account for the changing climate conditions, while maintaining the historical cropping patterns; (iii) unilateral water demand adaptation, where the farmers take into consideration the effects of climate change in the selection of the most profitable cropping patterns, while keeping the historical water supply operations; (iv) coadaptation option, where the nominal water demand is replaced by a dynamically updated water demand for every agricultural season according to the crops that are actually cultivated and to the current climate conditions.

Potential additional adaptation actions include improving the conveyance and distribution through the irrigation canal network to move towards on-demand irrigation delivery, changing the irrigation methods from border to sprinkler or microirrigation for improving the irrigation efficiency, or introducing new crop types, potentially including bio-energy crops. These represent interesting and viable options. However, they would involve investments in infrastructural changes such as capacity expansion, modification of the irrigation canals, or changes in farm machinery. On the contrary, the policy options that we analyzed are the most promising flexible and low-cost adaptation alternatives. In fact, these do not require any infrastructural or financial investment, but only an institutional and governance effort to promote information sharing for coordinating system management and renegotiating the farmers' water allocation plans on a more frequent, seasonal basis. A summary of the different climate scenarios and policy adaptation options considered in this study is reported in Table 1.

4. Numerical Results

4.1. Model Validation and Coadaptation in Current Climate Conditions

The aim of this section is first to validate the output of our CHNS model against historical data, then to assess the potential space for improving the current management policies via coadaptation of water supply

Table 1. Summary of the Policy Adaptation Options Analyzed

Policy Option	Water Supply	Water Demand
No adaptation baseline	Water supply operations designed wrt the nominal water demand and the historical climate	cultivation of the crops according to the historical land use
Water supply adaptation	Water supply operations designed wrt the nominal water demand and the projected climate	Cultivation of the crops according to the historical land use
Water demand adaptation	Water supply operations designed wrt the nominal water demand and the historical climate	Cultivation of the crops selected by the farmers under the projected climate
Coadaptation	Water supply operations designed wrt the actual water demand and the projected climate	Cultivation of the crops selected by the farmers under the projected climate

and demand. The validation of the baseline alternative with no adaptation option, which serves as an approximation of the current decision making processes, is crucial for contrasting the different adaptation policies under projected climate conditions, for which historical trajectories are not available.

The validation of the modeled lake regulation is reported in Figure 5. According to the adopted normative meta-modeling approach, the lake regulation is defined as an optimal operating policy balancing flood control (J^{flood}) and water supply (J^{def}). Solving this two-objective policy design problem yields a set of Pareto optimal alternatives (orange circles), whose performance is contrasted in Figure 5a against the historical one (gray circle). Results show that the historical performance is dominated by the Pareto optimal solutions as in our model we are focusing on two objectives only, while the real lake regulation is also driven by other minor interests such as navigation, tourism, and environmental flows. However, our baseline (dark red circle) is close to the historical performance and therefore successfully captures the lake operator's preferences among the two primary objectives. It is worth noting that the baseline is positioned on the left side of the Pareto front, which suggests that flood control is relatively more important than water supply (or, that it is easier to control floods than minimize the water supply deficit). The similarity of the historical regulation and the baseline is confirmed by the comparison of the observed and simulated trajectories of Lake Como level and release reported in Figure 5b for 2002, which was selected as representative of normal hydrologic conditions. Results show that the baseline regulation (dark red lines) is reproducing the historical one (gray lines), with some negligible differences in the low level period which do not affect the system performance. Furthermore, the trajectories of lake level and release obtained under the coadaptation option (blue lines) are also close to the historical ones, thus confirming that the proposed adaptation policy represents a flexible and feasible solution for the management of the Adda River basin, requiring only marginal changes in the historical management strategies.

Besides the lake regulation, the CHNS model includes 39 irrigation units in the Muzza irrigation district, where, according to the adopted normative meta-modeling approach, the cropping pattern is determined by the 39 modeled farmers as the most profitable one. The validation of the selected cropping pattern resulting from the simulation of the farmers' behaviors is reported in Figure 6 against the historical land use in the Muzza irrigation district. Results show that both the baseline and the coadaptation option provide decisions similar to the observed land use, particularly for maize and temporary grassland cultivation. Note that the baseline represents the main crops very well, while ignoring the minor ones (e.g., tomato, rice, and soybean). This is the direct effect of the assumption that the decision of each of the farmer in Problem (2) is restricted to a single crop, which leads to an intrinsic limitation in representing the entire possible range of cropping patterns. However, this hypothesis does not hinder the ability to capture the decisions on the main crops at the district scale.

The combination of the baseline operating policy with the baseline cropping pattern represents the current management of the Lake Como system. However, the observed climate trend (see Figure 3) suggests that the system is already experiencing the effects of climate change and is probably transitioning to an altered hydrologic regime, which could make the current policy setting suboptimal and inadequate for these new conditions. For this reason, we first contrasted the baseline alternative with the new equilibrium between water supply and demand achievable under the coadaptation policy option in historical climate conditions. The underlying idea is to check what would have happened historically if the water rights system were replaced by a dynamic allocation of the water based on the actual water requirements of the crops. Under the coadaptation policy simulated over 2004 (selected as representative of normal hydrologic conditions), the cropping pattern in the Muzza district changes as shown in Figure 6c, with the cultivation of maize

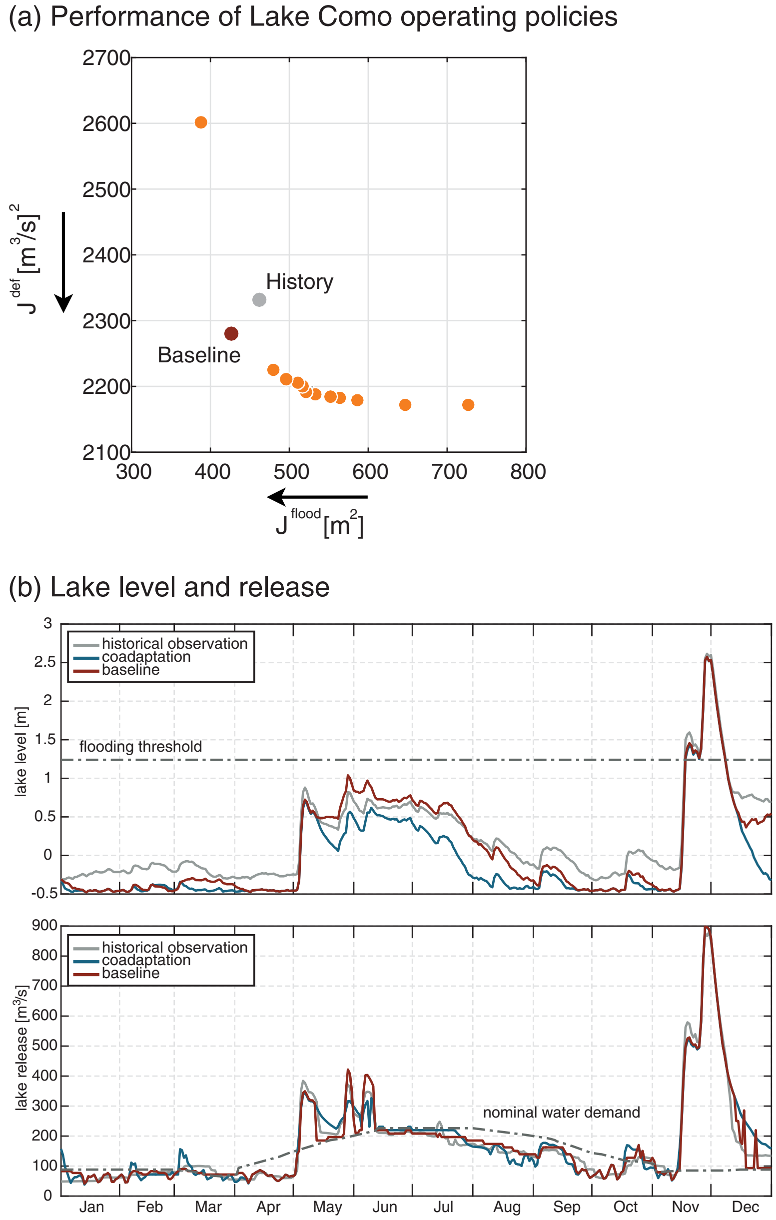

Figure 5. (a) Validation of the Lake Como operating policy via comparison of observed (history) and simulated (baseline) performance in terms of flood control J^{flood} and water supply deficit J^{def} against a set of Pareto optimal solutions. (b) Comparison of trajectories of the Lake Como level and lake release in 2002.

slightly reduced (from 80 to 74%) and replaced by rice (3.5%) and soybean (2.5%). The combination of these crop decisions with the adaptation of Lake Como operations with respect to the actual demand of the crops yields a net profit equal to 15.6 M€ in 2004, while the baseline alternative attains 14 M€ over the same year. The differences between these two policy options confirm that the hydrologic regime has probably been partially altered by a nonstationary climate trend. As a consequence, the baseline alternative, which is constrained by policy inertia, becomes inferior with respect to the coadaptation option.

In order to filter the variability of the hydrological regime and have a more reliable comparison, we repeated the experiments over multiple years, namely from 2001 to 2005, including two normal years (2002 and 2004), a wet year (2001), and two dry years (2003 and 2005). The values of net profit reported in Figure 7a show that the system performs slightly better across these years under the coadaptation option than under the baseline, with a larger gap in dry years (e.g., in 2005) than under normal or wet conditions (e.g., 2002).

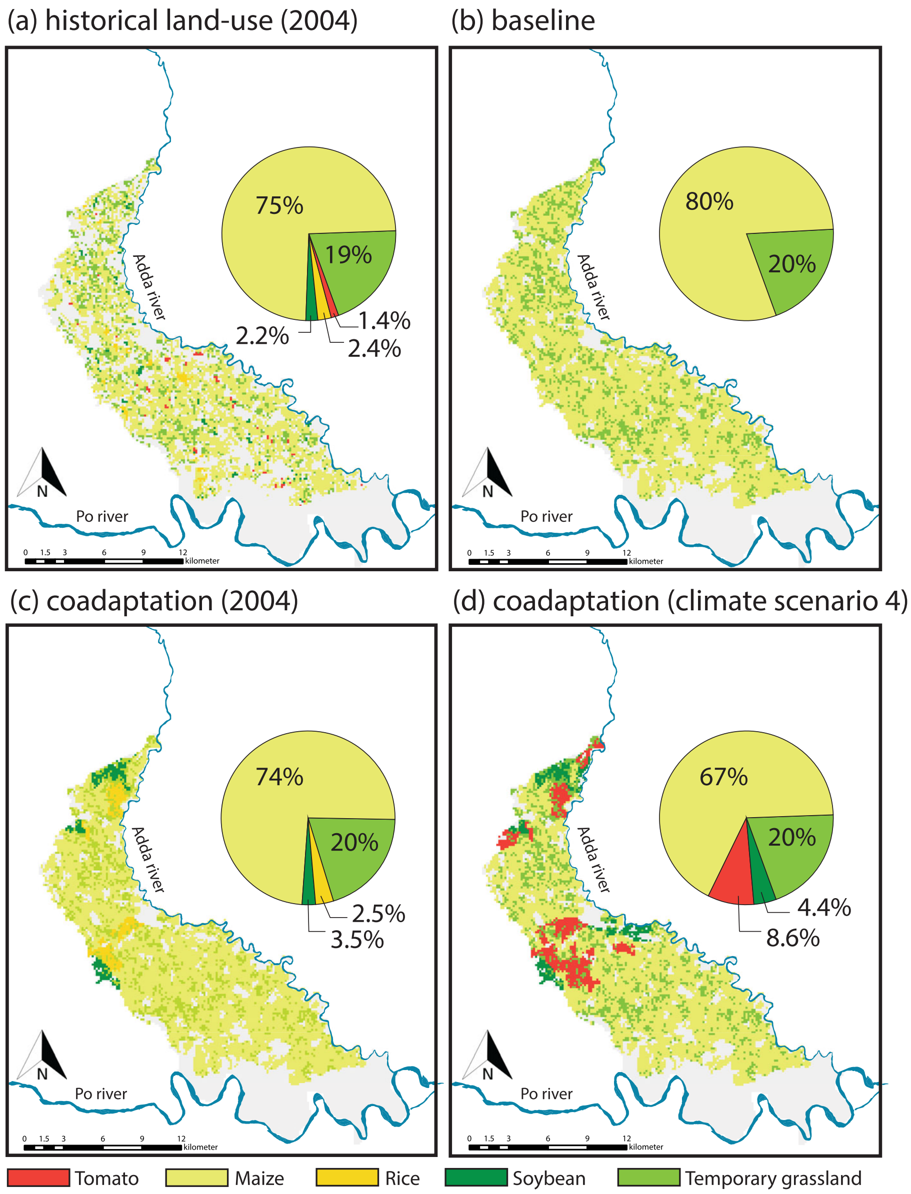

Figure 6. Land use map of the Muzza irrigation district: (a) reports the historical land use, (b) the calibrated land use under the baseline alternative, (c) the simulated land use in 2004 under the coadaptation option, and (d) the simulated land use in climate scenario 4 under the coadaptation option.

The difference between the two policy options becomes larger when considering water productivity (Figure 7b), which is defined as the ratio between the net profit and the total irrigation supply during the agricultural season [*Barker et al*., 2003]. Results show that the water productivity is 60% higher for the coadaptation option than for the baseline. This indicates a significant improvement in the overall efficiency of the agricultural water management practices, namely a higher crop production obtained with a smaller water supply, corresponding to a general reduction of the opportunity costs of irrigation in favor of other water uses in the system. However, these benefits may be insufficient to overcome the policy inertia of the decision-making authorities due to the less pronounced gains in net profit.

4.2. Coadaptation in Projected Climate Conditions

To assess the potential of the different policy adaptation options in reducing the negative consequences of policy inertia under more and more severe conditions, we analyze the system performance under projected climate scenarios. Figure 8a compares the current and projected climate in terms of Lake Como inflows. This

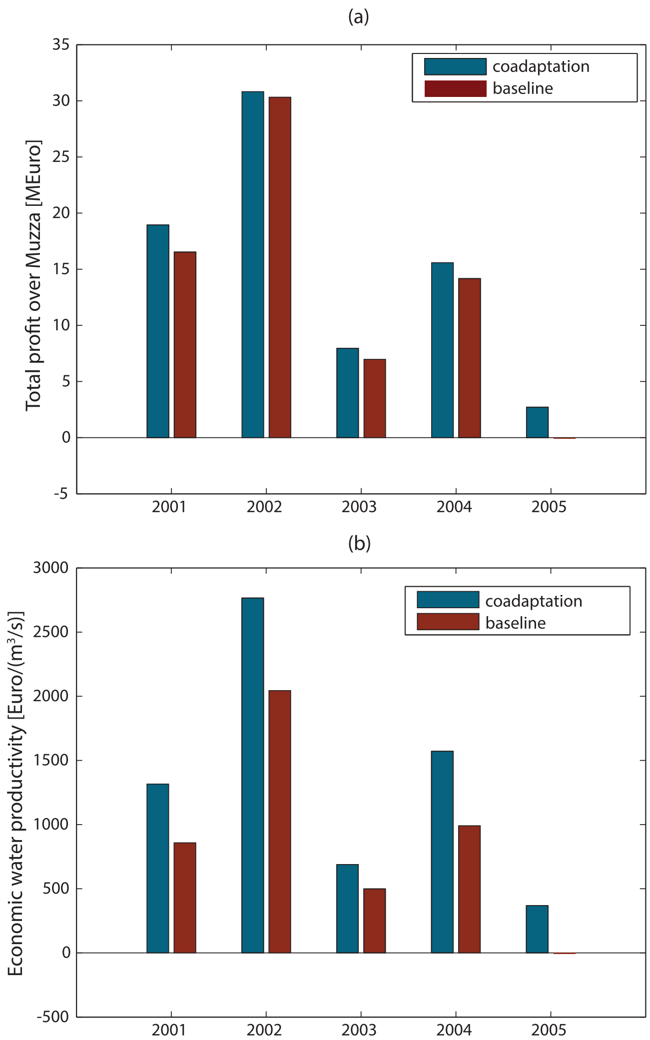

Figure 7. Comparison of (a) the total net profit and (b) the water productivity under the baseline alternative and the coadaptation policy option in current climate conditions.

figure highlights the crops' growing period (dashed gray line) and suggests that the projected conditions are expected to be very challenging due to very dry summers and higher inflows occurring only outside the crops' growing period. The five projected scenarios selected are at least as severe, if not worse, as 2005, a particularly drought year reported in the historical records.

Figure 8b reports the net profit obtained under the different policy adaptation options over 5 years representative of projected climate conditions (including dry, medium, and wet years), where the brown bars and the dark blue bars represent the no adaptation baseline and the full coadaptation of water supply and demand, respectively. The negative net profit indicates that the gross income from the crop yield is unable to cover the production cost of the crops, which may hamper the stability of the system. These results are obtained assuming that the subsides currently provided to the farmers as well as the crops' prices and cost will remain the same in the future. Our results suggest that the European Union will likely need to update the current system to ensure economically profitable agricultural activities. However, it is worth noting that this international intervention should be considered in combination to other adaptation options which are not explored in this work, such as the introduction of new crops or the modification of the irrigation system to increase the overall irrigation efficiency.

Figure 8b shows that the baseline alternative consistently attains the worst performance, with negative net profits in all the five scenarios simulated, with a cumulated net profit equal to −37 M€. On the contrary, the coadaptation of water supply and demand is the best performing option across all the scenarios. This positive result is obtained by negotiating and revising the water allocation plans of the farmers every agricultural season on the basis of the selected cropping pattern and adapting the daily water supply operations to the estimated water demand. In particular, Figure 6d shows that some farmers replace maize with tomato and soybean. These are both water demanding crops, but they are also more profitable than maize. Although they are not economically preferable under historical conditions, an adaptive management of the water supply system allows storing the anticipated precipitation in early spring to better support the irrigation during the period of high water demand. These combined decisions allow higher profits than under the baseline alternative, potentially avoiding the costs of policy inertia, which account for around 10 M€/yr. It is also worth noting that the values of profit attained in the five simulated scenarios are highly variable due to the increased hydrologic variability across these years (Figure 8a).

Finally, in addition to analyzing the full coadaptation of water supply and demand, we explored two intermediate policy options corresponding to the unilateral adaptation of the water supply and water demand,

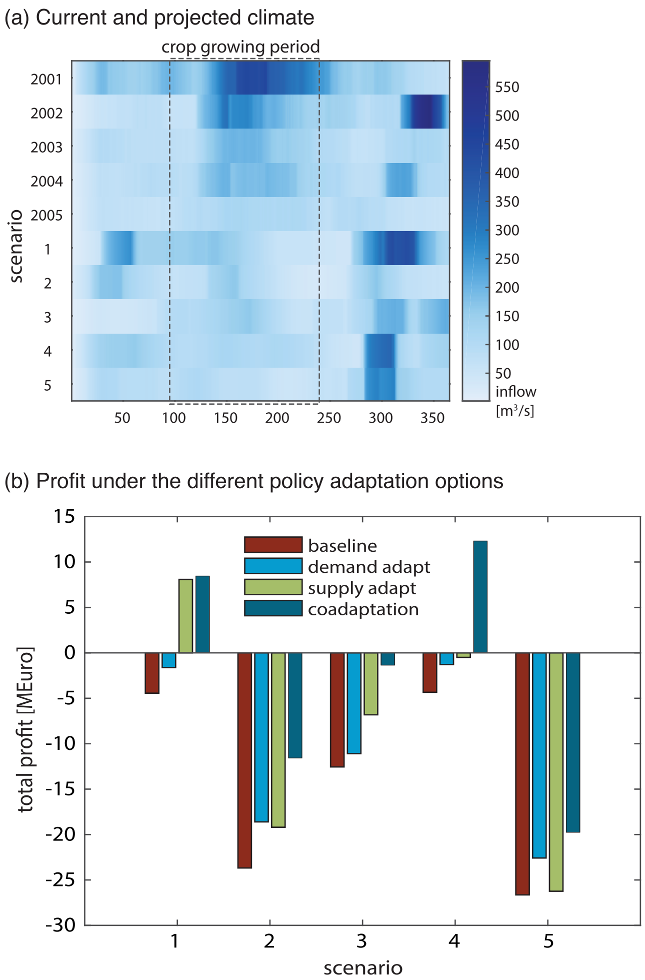

Figure 8. (a) Comparison of current and projected climate conditions. (b) Total net profit obtained under the different policy options in the five projected scenarios.

respectively. Figure 8b reports the performance of the water supply adaptation (light blue bars) and of the water demand adaptation (green bars) evaluated in terms of net profit under projected conditions. Results show that these unilateral adaptations improve the performance of the baseline alternative, but they are consistently outperformed by the coadaptation of water demand and supply, which is able to exploit the existing feedbacks between the two subsystems.

5. Discussion

5.1. Environmental Impact Assessment

The results discussed in the previous section focus on the system performance as measured with respect to the two primary economic sectors involved in the Adda River basin management, namely irrigation water supply and flood protection. Beside these sectors, the environment also plays an important role in the management of this CHNS, as the regulation of Lake Como must comply with a minimum environmental flow constraint equal to 5 m^3/s for the entire year to ensure adequate ecological conditions in the Adda River. However, since this constraint alone is likely to be inadequate for maintaining the natural ecological processes [*Jager and Rose*, 2003], in this section we compare the environmental impacts of the baseline against the coadaptation option by computing a variety of indicators related to both the ecosystems in Lake Como as well as in the Adda River. These indicators are evaluated under current and projected hydroclimatic conditions, as reported in the left and right panels of Figure 9, respectively.

Based on prior work [*Castelletti et al.*, 2006], the impacts on the lake environment can be quantified in terms of normalized distance of the lake level from natural conditions, defined as a cyclostationary mean computed over the period 1946–2000. Figure 9a shows that, not surprisingly, the lake regulation altered the natural conditions. However, the coadaptation option does not induce a further modification of the current conditions, with the values of the indicator for the baseline and the coadaptation option remaining almost equivalent over historical hydrologic conditions. In projected hydroclimatic conditions, the distance from the (historical) natural conditions slightly increases, while the differences between baseline and coadaptation remain limited. These results suggest that the proposed coadaptation option is not impacting the lake environment more than the current baseline regulation.

The assessment of the environmental impacts in the downstream Adda River is performed by using a subset of the 32 indicators of hydrologic alteration proposed by *Richter et al.* [1996] (see Figures 9b–9e). Overall, the values of this set of indicators show that the two alternatives do not induce significant environmental impacts, as the number of times they fall outside the 25th and 75th percentile values computed over the historical flows (the dashed lines in the figure) is similar. Particularly in normal/wet conditions (e.g., year 2001 and 2002 in the left column of the figure), the coadaptation option produces a higher number of

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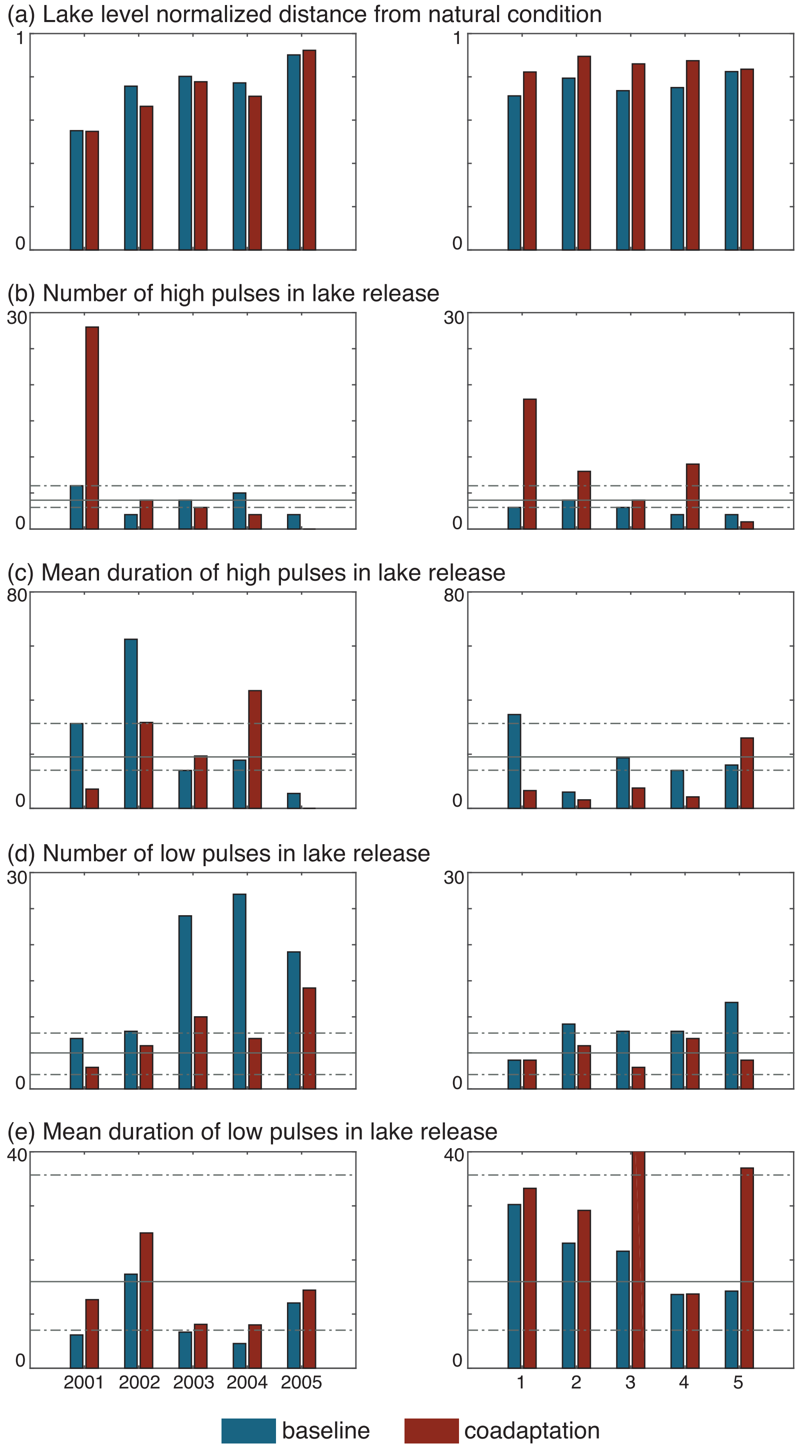

Figure 9. Environmental impact assessment on lake Como and downstream River Adda for baseline and coadaptation option in current (left) and projected (right) hydroclimatic conditions. The lines in Figures 9b–9e identifies the average (solid line) and the 25th-75th percentile values (dashed line) computed over the historical period.

shorter high pulses, while reducing the number of low pulses and increasing their duration with respect to the baseline. This strategy maximizes water productivity by reducing the water losses during high pulses, when the flow in the river is higher than the water requirement of the crops, and by limiting the stress on the crops induced by water scarcity during low pulses. These effects produced by the dynamic management of the coadaptation option, where water supply is matched to the crops' requirements, are confirmed by the values of the indicators in projected hydroclimatic conditions (right column of the figure), which amplify the relative difference between baseline and coadaptation. In particular, in conditions of increased water scarcity, the coadaptation option tends to further alter the number and duration of high pulses with respect to the baseline in favor of a reduction in the number of low pulses.

5.2. Performance of Adaptation Options for Different Drought Levels

The results reported in section 4.2 show that the different policy adaptation options attain different performance across the five projected climate scenarios (see Figure 8b). The unilateral adaptation of water supply performs better than the adaptation of the water demand in scenarios 1, 3, and 4, which represent less intense drought conditions than scenarios 2 and 5. In the latter scenarios, the unilateral water demand adaptation is instead preferable.

A tentative formalization of this relationship between system performance and drought intensity is provided in Figure 10. Drought intensity is measured in terms of inflow supply index (ISI), defined as

$$ISI = \frac{1}{n}\sum_{i=1}^{n} w_i \cdot Pr(Q_i), \quad (3)$$

where $Pr(Q_i)$ is the nonexceedance probability of monthly total inflow Q in month i considering the crops' growing period only, weighted by a factor w_i which accounts for the water demanding season. The smaller the ISI value, the more severe the drought event. This indicator was defined for characterizing drought events that are mainly related to a combination of agricultural droughts and hydrological droughts [*Mishra and Singh*, 2010], which cannot be captured by traditional indexes for meteorological drought such as the widely adopted Standardized Precipitation Index [*McKee et al*., 1993].

Results show that the baseline and full coadaptation are consistently the worst and best options, respectively. The two unilateral policy adaptation options attain intermediate performance, with the unilateral water supply adaptation performing close to the coadaptation option for high values of ISI (i.e., less severe droughts) by successfully exploiting the adaptive capacity of the lake operations to adjust the water supply to the changed climate conditions. This water supply adaptation option becomes less effective when the water availability is very low during the agricultural season and the lake capacity limits the volume of water that can be stored in the winter period. As a consequence, in such extreme drought conditions, acting on the water demand side of the problem becomes preferable to mitigate the expected economic losses, because it adapts cropping pattern decisions to these challenging dry conditions. This rank reversal between unilateral water supply or demand adaptation is clearly illustrated in Figure 10, where the water supply adaptation results to be preferable for ISI values higher than 0.15 and the water demand adaptation becomes more effective for ISI values lower than 0.15.

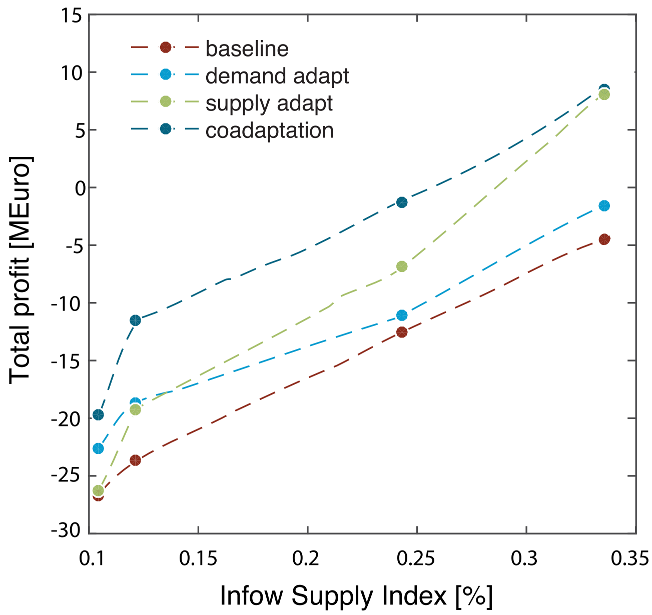

Figure 10. Relationship between the total net profit and the Inflow Supply Index under the different policy options. The more severe drought conditions during the growing period are characterized by smaller ISI values.

5.3. Dynamic Changes in the Preferences of the Lake Operator

The results discussed so far explored alternative policy adaptation options under the assumption that the preferences driving the decisions of the lake operator and the farmers will not change over time. This assumption likely holds for farmers, who will continue selecting the most profitable crops also in the future. However, the preferences of the lake operator may change while experiencing more

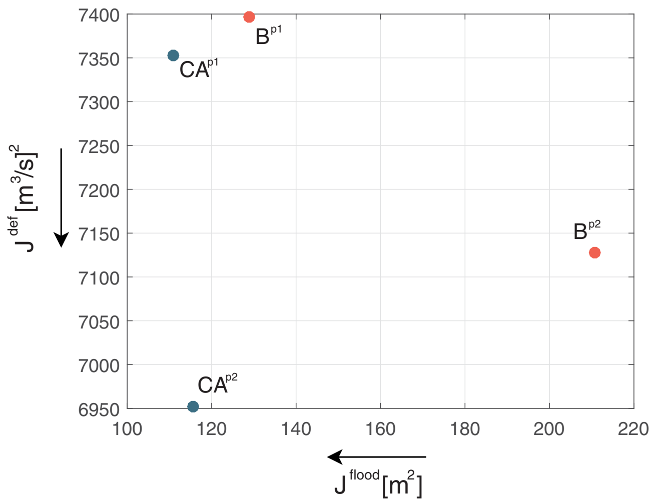

Figure 11. Comparison of the system performance in projected climate conditions evaluated in terms of flood control J^{flood} and water supply deficit J^{def} under the baseline and coadaptation options with historical (B^{p1}-CA^{p1}) and modified (B^{p2}-CA^{p2}) preferences of the lake operator.

frequent and intense droughts, moving the historical tradeoff between flood control and water supply in favor of the farmers. In this section, we explore the sensitivity of the system performance under projected climate with respect to a dynamic change of the lake regulation tradeoff from the historical one, which is more sensitive to flood control (see Figure 5), toward a new tradeoff more in favor to the irrigation supply.

The comparison of the system performance under the baseline and the coadaptation options for the historical and the new tradeoffs is illustrated in Figure 11. Results show that changing the preferences of the lake operator more in favor to the irrigation supply has a significant impact on the system performance, producing a reduction of the water supply deficit J^{def} equal to 3.5% under the baseline and 5.4% under the coadaptation option. However, the conflict between these two sectors implies that any improvement in terms of irrigation supply is paid in terms of flood control. In fact, the performance in terms of J^{flood} degrades of 60% under the baseline and 4.5% under the coadaptation options. This difference can be explained by the higher water productivity attained by the coadaptation option (see Figure 7), which uses less water for irrigation and, consequently, can maintain the water levels far enough below the flooding threshold to reduce flood costs.

6. Conclusions

Growing water demands and increasing uncertainties in the hydrologic cycle due to changes in climate and land use will challenge agricultural water resources management in the coming decades. This requires advancing our models of such complex systems in order to study how they will evolve under changing climate forcing and human decisions. This paper contributes an integrated modeling framework for exploring the potential coevolution of coupled human-natural systems under climate change, including a novel normative meta-modeling approach for better capturing human behaviors and their interactions with the natural system in order to project their coevolution under changing conditions. The application to the pilot study of the Adda River basin (northern Italy) allows simulating different policy adaptation options to quantify the potential space for improving the current water management strategies. The proposed coadaptation option, based on the seasonal negotiation of the water allocation plans of the downstream users and the simultaneous adaptation of the water supply operations, allows assessing the impacts and costs of policy inertia and quantifying the potential cobenefit of a more dynamic management of the CHNS.

Simulation results show that under current climate conditions, the flexibility provided by the coadaptation of water supply and demand increases the water productivity by almost 60% over the 5 years considered. This is the result of the dynamic adjustment, at the beginning of each agricultural season, of the water supply operations to match the changing downstream water demand. In turn, demand is determined by the revised water allocation plans of the farmers on the basis of the expected irrigation requirements of the cultivated cropping patterns, which are selected to maximize the expected farmers' profit at the end of the agricultural season. However, the benefit of adopting the coadaptation option under historical climate is less pronounced when evaluated in terms of net economic profit, thus justifying the lack of incentive to modify the status quo. Such inertia is confirmed by the analysis of the historical land use, which shows negligible changes over the last 10 years. The analysis of the historical practices under projected climate conditions, characterized by more intense and frequent droughts, shows that the sustainability of the current agricultural practices in the Adda River basin is a significant concern. These adverse climate change impacts can be mitigated through the dynamic coadaptation of water supply and demand. This policy option would allow avoiding potential losses for an estimated value of more than 10 M€/yr, representing 70% of the expected annual losses. Unilateral adaptation of either water supply or demand are demonstrated to be both less effective than the full coadaptation option, though attaining better performances than the baseline no-adaptation alternative. Results suggest that the effectiveness of the different policy options varies as function of drought intensity, with water demand adaptation outperforming water supply adaptation under severe drought conditions. Finally, we show how the system performance is sensitive to possible dynamic changes in the preferences of the lake operator. Moving the tradeoff between flood control and irrigation supply more in favor of the latter may produce significant additional benefit for the farmers at the cost of increasing flood damages.

Our results suggest the need of future research focusing on the following open points: (i) assessing the acceptability for stakeholders of the coadaptation option and the associated negotiation of water allocations on a seasonal basis [*Adger et al*., 2009] and exploring the sensitivity of the system performance to alternative frequencies of the negotiation process (e.g., replacing the seasonal coadaptation with a longer time horizon spanning two or more years); (ii) enlarging the set of adaptation options available, possibly including the introduction of bio-energy crops [e.g., *Ng et al*., 2011], in order to identify solutions which might better contribute to the mitigation of the impacts of climate change in the Adda River basin, ultimately supporting the future sustainability of the agricultural activities; (iii) better analyzing the role of the socio-economic dimension of the problem and the impacts of variations in the total water demands as well as in the cost and price of the crops [e.g., *Finger*, 2012].

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